Negative priming 1985 to 2015: A measure of inhibition, the emergence of alternative accounts, and the multiple process challenge.

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A measure of inhibition, the emergence of alternative accounts, and the multiple process challenge.

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Abstract

In this article three generations of authors describe the background to the original article; the subsequent emergence of vigorous debates concerning what negative priming actually reflects, where radically different accounts based on memory retrieval were proposed; and a re-casting of the conceptual issues underlying studies of negative priming. What started as a simple observation (slowed RTs) and mechanism (distractor inhibition) appears now to be best explained by a multiple mechanism account involving both episodic binding and retrieval processes as well as an inhibitory process. Emerging evidence from converging techniques such as fMRI, and especially EEG, is beginning to identify these different processes. The past 30 years of negative priming experiments has revealed the dynamic and complex cognitive processes that mediate what appear to be apparently simple behavioural effects.

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The initial research issue concerned how action can be selectively directed towards a relevant object in complex environments containing other objects competing for the control of action. One solution that would enable action to be directed towards an appropriate object at the right moment in time involves active inhibition of competing distractor representations. It was proposed that this inhibition could be observed by presenting a previous distractor as a target object shortly afterwards. If response to a target that was just previously a distractor requires access to recently inhibited information, then responses ought to be slowed. This inhibitory effect was termed negative priming (Tipper, 1985).

There has been extensive research on the topic of negative priming over the past three decades, and several excellent reviews of the negative priming (NP) literature (e.g., Fox, 1995; May, Kane & Hasher, 1995; Mayr & Buchner, 2007). In particular, a very recent review by Frings, Schneider and Fox (2015) has carefully considered research conducted over the 20 years subsequent to the two reviews published in 1995. Therefore when asked by the current editor of QJEP to write an article for a special issue, it was not clear what contribution this paper could make. A comprehensive review of the literature would be somewhat redundant in light of the excellent review published recently (Frings et al., 2015). Hence this article aims instead to provide an historical and personal background concerning the emergence of the 1985 paper, a brief summary of the emergence of alternative accounts, and a discussion of how the challenge of an effect driven by multiple processes might be met.

Negative priming: A measure of inhibitory selection processes

When Tipper applied to do his PhD at Oxford University he was interested in the problem of selection-for-action. That is, with complex perceptual inputs where many objects could be present and competing for the control of action, how was action directed to the appropriate object at the appropriate moment in time? This was of course a long-standing issue (e.g., Broadbent, 1958) and the dominant view at that time was the spotlight account. The basic idea was that early perceptual inputs were represented in parallel. An attentional spotlight could then move across a map of these inputs, and facilitate the processing of stimuli that it highlighted. There were two salient features of this model: first, competing internal representations of the distractor objects were presumed to decay passively, and second, the spotlight was presumed to be spatial in nature, moving from one location to another.

However, Tipper wondered whether these properties of the spotlight account were correct, in particular whether there could be a dual selection process. That is, rather than target stimulus activation being increased by the spotlight and distractor representations passively decaying in activity, perhaps distractors were actively inhibited. Certainly this dual process model, excitation of the target representations and simultaneous inhibition of competing distractors, would be much more efficient, better explaining the rapidity with which selection could be achieved; and of course it better matched the building blocks of interactions between excitation and inhibition in the brain.

Curiously, after arriving in Oxford he initially forgot about the idea of active inhibition of distracting information. Rather, Tipper became intrigued by the priming literature. Attending to a stimulus could produce positive priming effects, facilitating processing of the same or a

semantically related stimulus (e.g., Carr, McCauley, Sperber & Parmelee, 1982; Meyer, Schvandeldt & Ruddy, 1975). Such observations proved to be useful for models such as spreading activation in semantic networks. However, what he found especially intriguing was the work of Tony Marcel who was reporting demonstrations of subliminal priming effects (Marcel, 1983). That is, a prime stimulus such as a word could be pattern masked so that participants were unaware of its identity, but nevertheless it could still produce semantic priming effects on a subsequently presented word. These observations supported ideas of sophisticated processing, such as reading for meaning, without conscious awareness (e.g., Dixon, 1971).

But Tipper noted a gap in the market, where he thought he might get a publication, and maybe even a PhD. Although there was a large literature investigating priming when people could attend to supraliminal primes, and emerging evidence for subliminal priming, there was little work examining the effects of primes that were ignored while selecting a target for action. Hence experiments were designed where participants were presented with two drawings of everyday objects. These objects were superimposed, one being red, which was the target to be reported, and the other green, which was the distractor to be ignored, or vice versa (see Figure 1 of the accompanying article). Tipper felt that although participants were typically unaware of the identity of the green distractor, reflecting the remarkable efficiency of the selection processes, the distractor must nevertheless be encoded. Furthermore, he assumed that active representations of the encoded distractor ought to produce positive priming effects, facilitating processing of a subsequent target requiring those same representations. For example, if a picture of a table was ignored in a prime display, processing of the same picture presented in a probe display a few seconds later ought to be facilitated, as observed in other priming techniques.

Of course, we now know the opposite result was observed. After ignoring a picture, processing of the same picture shortly afterwards was impaired. Initially Tipper was somewhat baffled by this new finding, and didn't actually believe it could be true. Hence a replication and extension study was undertaken, which also produced this slowing of response. It was some days later, during the mid-morning coffee break in the Psychology department, that it suddenly dawned on him: Of course, this impaired processing of a subsequent probe could reflect the inhibition of distractors that was initially proposed when applying for the PhD in the first place.

This was a slightly odd situation. Exactly the right experiment was undertaken to test the distractor inhibition hypothesis, even though Tipper had been side tracked by his new interest in priming effects, and was no longer thinking about inhibition. This seemed like rather a coincidence. However, there was a further point in the first experiment that was also crucial. In those days computers were somewhat rare and exotic devices, and experiments were still being conducted with tachistoscopes. For this particular experiment, the materials presented in the tachistoscope were hand drawn using red and green pens (quite a demanding task for a color blind experimenter). There were two sets of cards: The primes contained the red target and green distractor, while the subsequently presented probes only contained red targets. The experiment was ready to start, but the evening before Tipper decided that maybe it would be better to maintain the selection processes constant within a trial, with a red target selected from a competing green distractor in both the prime and the subsequent probe display. So he added green distractors to the probe display at the last minute.

Selection in the probe display turned out to be critical in this experiment, and in many subsequent studies of negative priming. In these studies, when selection of a target from a distractor in the probe is required, then negative priming is observed. In contrast, if no probe

selection is required, then no priming, or even facilitation is often observed (D'Angelo & Milliken, 2012; Lowe, 1979; Milliken, Thomson, Bleile, MacLellan, & Giammarco, 2012; Moore, 1994; Tipper & Cranston, 1985; but see Frings & Spence, 2011; Frings & Wentura, 2006; Moore, 1994; Milliken, Lupianez, Debner & Abello, 1999; Neill, Terry & Valdes, 1994). Hence, although it is now clear that not all procedures used to measure negative priming require probe selection, if this last minute change had not been made to the specific task described above, we would not be writing this paper now.

It turned out there were previous reports of similar effects in the literature. As far back as 1966, Dalrymple-Alford and Budayr investigated a range of Stroop colour word conditions, one of which was a trial where the previously ignored word was the same as the subsequent to-be-named ink colour on the next trial. They noted that performance in this condition was slower than in a baseline condition in which there was no relationship between the prime and probe display. Subsequently Greenwald (1972), Neill (1977) and Lowe (1979) replicated and extended these effects. It is not clear why there was little interest in this topic until after the Tipper (1985) paper. Perhaps the imagination of readers was caught by the demonstration of semantic negative priming effects, where ignoring a picture (e.g., cat) that was semantically related to a subsequent target (e.g., dog) also slowed responses (see Figure 2 in the accompanying article – interestingly, semantic negative priming effects have proven to be somewhat difficult to produce with other methods; see Chiappe & MacLeod, 1995; MacLeod, Chiappe & Fox, 2002). In any case, the point to note is that the negative priming effect reported by Tipper (1985) was not without precedent in the literature.

It was decided that a label describing the effect and highlighting its contrast with other priming effects would be useful. Initially "inhibitory priming" was pondered. However, it was

felt that this label was too theoretically loaded, as perhaps future studies would show that the impaired processing did not reflect inhibitory selection mechanisms, the right decision in hindsight. Therefore "negative priming" was felt to be more neutral, simply describing the slowed processing of subsequent probes, contrasting with the "positive priming" literature where processing of subsequent probes was facilitated. Interestingly, other authors (e.g., Mayr & Buchner, 2007) felt that "negative priming" reflected a particular explanatory construct, and indeed was a "saucy" label. Although the label seems to have spiced up the lives of some academics, at least it helped to link an increasingly divergent literature over the subsequent years.

Over the next few years new studies focused on identifying further properties of negative priming, such as the level of processing received by distractors, and the nature of representations upon which the inhibition acted. In terms of the level of processing of distractors, Tipper and Driver (1988) demonstrated that even when a picture was ignored and the subsequent probe was a word, negative priming was observed. Such a result further supported the idea that inhibition was associated with semantic properties of a stimulus and not with early perceptual features. A further study (Tipper, McQueen & Brehaut, 1988) demonstrated that the effect could also be detected when response to the prime was a finger key-press, and response to the subsequent probe was verbal naming, and vice versa. The transfer between response output systems also supported a central locus for the inhibition. And finally, new data challenged the core idea that selection was achieved via moving a spotlight over a spatial map. When a competing distractor stimulus moved, disappeared behind an occluding surface, and then reappeared, negative priming was still observed when a response was subsequently directed to it. This observation confirmed that the mechanisms underlying negative priming were object-based, and able to move with a distractor object (Tipper, Brehaut & Driver, 1990).

However, the idea that the putative inhibition process might be fixed at a semantic level of encoding changed quite quickly. It was later argued that inhibition of competing distracting information was not fixed at a specific point in the flow of information from perception to action. Rather, inhibition was flexible, selectively suppressing information that specifically competed for the control of action. For example, in a selective reaching task (Tipper, Lortie & Baylis, 1992) it was demonstrated that distractors closer and ipsilateral to the reaching hand competed more and hence required greater levels of inhibition to achieve the goal of grasping the target object. Indeed, inhibition appeared to be hand-centered, based on the spatial position of the reaching hand. As the hand moved to new starting locations, the pattern of negative priming completely changed, even though all other frames of reference (e.g., retinotopic, head or body-centered) remained constant (see Figure 1). In sharp contrast, in tasks requiring semantic processing, such as classifying the superordinate category of an object, semantic information competed and was suppressed.

Insert Figure 1 about here

The demonstration of negative priming effects in more real-world situations, where people actually reach out and touch target objects in the presence of competing distractors (Tipper et al, 1992), is curiously neglected in many of the subsequent accounts. That negative priming reflected competition for action was also demonstrated by presenting obstacles in front of objects (Tipper, Meegan & Howard, 2002). Reaching around the obstacle significantly slowed down responses. When this stimulus was a distractor to be ignored, its competition for the

control of action was reduced, as reflected in less interference; hence less inhibition was required, as reflected in reduced NP. These results may also be interpreted in terms of action 'affordances', whereby interference occurs only for actions that are possible to produce (Wesslein, Spence, & Frings, 2015). Such action-centred processes can even be detected when observing someone else selectively reach for a target while ignoring a distractor (Frischen, Loach & Tipper, 2009), providing evidence for the simulation of another person's selection processes, as predicted by mirror systems. Such studies have greater ecological validity and appear to provide some evidence for the role of inhibition in the selection-for-action problem, and may be worth reconsideration in future investigations.

During this period in the early 1990s, Tipper collaborated with George Houghton. Houghton had been developing computational models of language, and together they realized that similar selection processes might be required across a range of situations, which led them to apply Houghton's ideas to the selection-for-action problem. This was the first attempt to formally describe the inhibitory processes that enable selective action. The model described a reactive inhibition process, where the inhibition was adjusted automatically to deal with distractors of different potency via self-feedback mechanisms. An emergent property of this model was that it also accounted for inhibition of return effects (Posner & Cohen, 1984), a closely related attentional inhibition phenomenon (e.g., Milliken, Tipper, Houghton & Lupiáñez, 2000). It could be argued that Houghton and Tipper (1994) was one of the more important papers published on the topic of negative priming; the formal computational model was capable of simulating existing negative priming effects and made numerous predictions that were subsequently confirmed. This model has also provided a framework for studies on selection more generally, beyond that focus solely on negative priming (e.g., Frings, Wentura, & Wühr, 2012;

Frings & Wühr, 2014). And although it was a book chapter that is not easily accessed, it nevertheless had, and continues to have (e.g., Wyatt & Machado, 2013), a wide impact.

Negative Priming: The role of episodic memory

Much of the early research on negative priming followed a convention for interpreting priming effects introduced in seminal studies of word identification (Morton, 1969; Scarborough, Cortese & Scarborough, 1977). Specifically, word identification was assumed to hinge on the activation state of a corresponding abstract lexical representation reaching a threshold value. By this view, prior presentation of the same word gives activation a 'head-start' toward that threshold value. By this same logic, an inhibition process might suppress the activation state of a lexical representation below baseline levels, effectively producing the opposite of a head-start toward the threshold value.

However, by the early 1990's, Logan's (1988) instance theory of automaticity had encouraged an alternative view. In particular, researchers had begun to entertain the idea that priming and other related cognitive phenomena might hinge on the retrieval of specific episodic representations of prior experience, rather than on the activation and inhibition of abstract knowledge representations (see also Brooks, 1978; Hintzman, 1986; Jacoby & Brooks, 1984; Medin & Schaeffer, 1978).

In the case of negative priming, there were hints of this shift in framework even before it was introduced formally to the literature. In particular, in a study focusing on the time-course of negative priming effects, Tipper, Weaver, Cameron, Brehaut and Bastedo (1991) somewhat surprisingly found that negative priming effects did not diminish in magnitude with increases in

the temporal interval between prime and probe. These results led Tipper and colleagues to speculate that ignoring a distractor might not merely result in a transient suppression of its abstract representation, but rather ignoring a distractor might fundamentally alter the long-term memory representation of that experience.

Neill and colleagues (Neill & Valdes, 1992; Neill, Valdes, Terry & Gorfein, 1992) took the field an important step further, and formalized an episodic retrieval account of negative priming. Drawing from Logan's (1988) instance theory, they proposed that prime encoding involves the binding together of semantic/perceptual information with response information. As a result, the episodic representation of an ignored prime distractor might include some form of code indicating that the item was ignored. Although it was not clear how this coding would take place, it seemed possible that an inhibitory tag (e.g., "ignore this stimulus") could be linked together with other perceptual and semantic codes for the prime. Onset of a probe target that matched the previous distractor would then result in the retrieval of this prime episode. The mismatch between the current requirement to attend and respond to the target, and the retrieved response information for that same item ("ignore this stimulus"), would then be responsible for negative priming.

In support of this episodic view, Neill et al. (1992; Neill & Valdes, 1992) reported that the time course of negative priming is not related merely to the interval between prime and probe, but also to the interval between a prime and the most recent preceding probe. In other words, these results demonstrated that negative priming can hinge on the temporal distinctiveness of the encoded prime episode. In theory then, negative priming could last for an arbitrarily long duration, as long as the probe cues the retrieval of an episodic representation of an ignored prime. Indeed, DeSchepper and Treisman (1996) subsequently reported negative priming effects in a

same/different classification task with nonsense geometric shapes that lasted as long as a month. Other studies have since reported negative priming effects that depend on the contextual similarity of prime and probe, a finding that strongly implicates retrieval of the prime episode in negative priming (Fox & deFockert, 1998; Grison, Tipper & Hewitt, 2005; Neill, 1997). Together, these results and others offer good support for the view that episodic retrieval can contribute to negative priming.

An episodic approach assumes that priming effects are the product of an encoding/retrieval interaction. This principle fits with the troubling finding noted above, that negative priming often hinges on the selection requirements of the probe task (Lowe, 1979; Moore, 1994; Neill et al., 1994; Tipper & Cranston, 1985). In a study aimed at highlighting the importance of this property of negative priming, Milliken, Joordens, Merikle and Seiffert (1998) demonstrated that a single ignored prime word (as well as a briefly presented and pattern masked single prime word) can produce negative priming, as long as the following probe requires selection between a target and distractor. One implication of these results is that negative priming is not limited to a specific set of prime encoding requirements that involve selective attention between a target and distractor. Rather, there appear to be an array of prime-encoding/probe-retrieval interactions that produce negative priming.

In line with this idea, Neill and Mathis (1998; see also Wood & Milliken, 1998) expanded on the original episodic retrieval hypothesis by suggesting that negative priming constitutes an example of "transfer inappropriate processing." The transfer appropriate processing principle was introduced by Morris, Bransford and Franks (1977) to describe the dependence of remembering performance on the particular demands of the remembering task, and the consistency of those task demands with the processing of the study items. In general, the

idea was that negative priming could result from such processing inconsistencies, broadly defined, rather than from the specific inconsistency of ignoring a prime, and then attending to an identical or related probe. Subsequent studies that have demonstrated a role for stimulus-response binding mismatches in negative priming comfortably fit within this transfer (in)appropriate processing framework, although some might prefer that a stimulus-response retrieval account remain separate from this broader view (Rothermund, Wentura & de Houwer, 2005; see also Frings et al., 2015).

Application of the transfer appropriate processing principle to negative priming comes with both benefits and costs. On the one hand, a benefit of the transfer appropriate processing framework is its potential as an organizing principle for large amounts of data that cross paradigm boundaries. A single principle that can accommodate a wide array of data from multiple experimental paradigms is ultimately quite powerful. At the same time, a cost of the transfer appropriate processing framework is that the negative priming effect no longer constitutes a specific tool to study the ignoring of distraction. If ignoring-and-then-attending is one of many diverse processing inconsistencies that produce inappropriate transfer, then the negative priming effect loses its utility as a tool to study the ignoring of distractors. Suffice it to say that studies of episodic contributions to negative priming unearthed a more complex link between effect and mechanism than originally envisioned (see Tipper, 2001).

Negative Priming: A measure of more than one process?

One source of the conceptual complexity associated with the NP effect is that it may involve more than one process. This is not a novel observation; it has been made routinely in the literature going back to the two review papers published in 1995 (Fox, 1995; May, Kane &

Hasher, 1995), and was echoed in the recent review by Frings et al. (2015). Our aim here is to draw attention to a particular dual process framework that may be useful in future work on negative priming. This framework identifies two relatively broad processing principles, each of which may capture aspects of performance to varying degrees across a wide array of tasks. The processing principles should not be thought of as aligned with particular types of tasks; we assume that one or both principles may be operative in all tasks used to measure NP. A noteworthy implication is that NP effects in identification and spatial localization variants of the NP procedure are attributed to the same processing principles.

Consider the spatial localization variant of the NP procedure introduced by Tipper et al. (1990). This procedure presents participants with four marked locations (e.g., lines or boxes to mark locations at which targets can appear), with a target stimulus (e.g., an 'O') appearing at one of the locations and a distractor (e.g., an 'X') appearing at a second location (see Figure 2). In the ignored repetition (IR) condition, a target 'O' in the probe display appears in the location occupied by a distractor 'X' in the preceding prime display. Performance in this condition is compared to that in a control condition in which the probe target and distractor appear in locations that were unoccupied by the prime target and distractor. Tipper et al. noted that performance was slower in the IR condition than in the control condition, and they attributed this effect to inhibition of the prime distractor object.

Insert Figure 2 about here

Park and Kanwisher (1994) subsequently reported a study that challenged the distractor inhibition account of this effect. They noted that the probe target 'O' in the IR condition appears in a location occupied by a different identity (i.e., the 'X'). As such, rather than distractor inhibition, this NP effect could be due to the mismatch in identities that are bound to a single location across prime and probe trials (see also Kahneman, Treisman and Gibbs, 1992 for a similar account). However, subsequent studies (e.g., Milliken, Tipper & Weaver, 1994; Tipper, Weaver & Milliken, 1995) demonstrated that NP can occur even when the ignored distractor and subsequent target are perceptually identical. Hence, although perceptual mismatches may produce a performance cost, they cannot be the only source of NP.

Hommel (1998) later showed that it is not just location-identity mismatches in spatial localization tasks that produce performance costs. Rather, binding mismatches generally, including those that involve diverse stimulus and response codes, can impair performance in many straightforward trial-to-trial priming procedures. These results led Hommel to extend the object file framework introduced by Kahneman et al. (1992) to event files, or episodic representations defined by bindings of both stimulus and response codes. A vast amount of empirical evidence has now accumulated in support of this view (e.g., Hommel, 2004; Hommel, Müsseler, Aschersleben & Prinz, 2001). Of particular relevance here, Rothermund, Wentura and DeHouwer (2005) demonstrated that incidental retrieval of stimulus-response associations can contribute to NP effects.

All told, it seems clear that episodic binding mismatches can contribute to both spatial and non-spatial NP effects, whether through prime-probe mismatches in perceptual codes or some combination of perceptual and response codes. By this view, onset of a probe cues the retrieval of a prime episode in which the recently created bindings may be either consistent or

inconsistent with those needed to respond correctly to the probe. If consistent (appropriate) bindings are retrieved then performance will be facilitated relative to a control condition. If inconsistent (inappropriate) bindings are retrieved then interference will slow performance relative to a control condition. Described in this manner, these episodic binding and retrieval effects appear to fit with the broad transfer (in)appropriate processing principle.

However, as noted above, a drawback to attributing NP effects wholesale to episodic binding and retrieval processes is that NP effects lose their utility as tools to study attention processes. Might another process, one that has an attentional function, also contribute to NP? A candidate attentional process that may contribute to NP is one that produces the inhibition of return effect in spatial orienting (Posner & Cohen, 1984). Inhibition of return is commonly attributed to an attentional process that biases orienting in favour of novel events over events that have recently been attended. Here we entertain the possibility that such a process might contribute to NP above and beyond the putative influences of episodic binding and retrieval outlined above. Although this idea has been forwarded previously to account for spatial NP (Christie & Klein, 2001; Milliken et al., 2000; but see Buckolz, Fitzgeorge & Knowles, 2012), we propose here that it may also apply to non-spatial forms of NP.

Consider first the attended repetition (AR) effects that occur in studies of spatial NP. Recall that an AR trial is one in which the location of a probe target matches that of a prime target. If the process responsible for inhibition of return contributes to performance in studies of spatial NP, then it follows that it should slow performance for AR trials. And if this were the case, then performance for AR trials might well look a lot like that for IR trials; that is, performance for both of these conditions would be slow relative to a control condition. Indeed, this result has been observed in several studies (e.g., Christie & Klein, 2001; Milliken et al.,

2000; Shapiro & Loughlin, 1993). Furthermore, the simplest account of this result is that performance is slowed in the AR and IR conditions for one and the same reason, by an attentional bias that favours encoding of novel over previously attended events (Houghton & Tipper, 1994; Milliken et al., 2000; Christie & Klein, 2001).

Yet, it has been clear from the outset that a single process could not possibly account for both AR and IR effects in all experimental contexts, because AR and IR effects often differ substantially (e.g., Tipper et al., 1990). In particular, AR trials often produce positive priming while IR trials produce negative priming. The key issue concerns how to interpret AR trial performance that varies from positive to negative priming across experimental contexts, while IR trial performance more consistently reveals negative priming. A straightforward solution is to assume that performance in both AR and IR conditions measures the joint influence of two processes on performance: (1) episodic binding and retrieval processes that typically facilitate performance on AR trials and interfere with performance on IR trials, in accord with notions of transfer appropriate processing; and (2) an inhibitory process that biases attentional orienting, and thus perceptual encoding, in favour of novel events. By this view, both AR and IR conditions might be affected by both of these processes. Further, if one assumes that the contribution of episodic binding and retrieval to performance varies from one experimental context to another, in accord with subtle changes in task demands, then a wide array of data patterns are possible (e.g., Milliken, Tipper & Weaver, 1994).

All told, we have highlighted two processes that may jointly contribute to a complex array of results that have been reported in spatial NP studies: (1) episodic binding and retrieval processes that produce effects on performance that are consistent with the transfer (in)appropriate processing principle (Morris, Bransford & Franks, 1977; see also Neill & Mathis,

1998; Wood & Milliken, 1998); and (2) an attentional orienting process that favours perceptual encoding of novel events (Posner & Cohen, 1984). As described, it would appear that this particular dual process proposal could only possibly apply to spatial NP effects, as inhibition of return is widely regarded to be an effect limited to spatial orienting. However, there are a growing number of studies that have reported inhibition of return-like results in studies aimed at non-spatial stimulus repetition (Hu & Samuel, 2011; Francis & Milliken, 2003; Law, Pratt & Abrams, 1995; Spadaro, He & Milliken, 2012), and a growing number of theoretical treatments of inhibition of return that point to broad mechanisms that favour orienting to novelty (e.g., Dukewich, 2009; Lupiáñez, 2010). As such, a dual process framework worth pursuing is one in which episodic binding and retrieval processes on the one hand, and an inhibitory attentional mechanism that favours encoding of novel events on the other hand, together contribute to both spatial and non-spatial NP effects.

Negative Priming: Meeting the multiple process challenge

The idea that NP effects in behavioural studies have more than one cause makes it problematic to link behavioural effects with underlying mechanisms. One way to meet this challenge is to look for converging evidence from measures of brain activity. Indeed, the past decade or so has seen the emergence of literatures on both EEG and fMRI studies of NP. As the fMRI literature is still relatively early in its development, we focus here on studies that have used EEG to measure ERP correlates of behavioural NP effects to meet the multiple process challenge. Our discussion also focuses on how EEG studies ought to be designed to address the specific dual process proposal discussed in the previous section. The interested reader will find a useful review of both the EEG and fMRI literatures in the Frings et al. (2015) review article.

The fine temporal resolution offered by EEG holds the potential to tease apart mechanisms that contribute to performance at different points in time. If we know when (and perhaps where) certain processes ought to produce their effects, EEG data may be able to arbitrate whether a behavioural effect is caused by one or another process. Indeed, researchers have attempted to capitalize on this potential by looking at ERP correlates of NP to see whether the "when and where" of those ERP correlates fit better with one or another theoretical framework.

To this end, some researchers have proposed that inhibition ought to impact processing relatively early after stimulus onset (e.g., Frings & Groh-Bordin, 2007; Mayr, Niedeggen, Buchner, & Pietrowsky, 2003)[1]. One basis for this proposal is an enhanced N200 component in frontal areas for incompatible flanker trials (Yeung, Botvinick, & Cohen, 2004), which presumably reflects an increased need for response inhibition on these trials. Translating this effect to a negative priming task, a probe target that matches an immediately preceding prime distractor is apt to be particularly vulnerable to interfering effects of an accompanying probe distractor, which in turn would invite an up-regulation of response inhibition.

In contrast, it might be argued that retrieval of a prime episode would occur at a longer latency following probe onset[2]. By this view, NP effects caused by episodic binding and retrieval ought to be captured by later ERP correlates that reflect comparison and evaluation of sensory stimuli with information retrieved from memory. This proposal fits with the view that

[1] Note that an argument can be made for later ERP components for inhibition, if operating at the level of response execution, as is observed in the stop-signal paradigm (e.g., Verbruggen & Logan, 2008).

[2] In contrast to this argument, it has been argued that episodic retrieval can influence current processing automatically, allowing for a rapid by-pass of slower response computation (e.g., Logan, 1988).

although context-free retrieval may be quick, context-dependent retrieval that underlies recollection of particular episodes occurs more slowly (e.g., Boldini, Russo, & Avons, 2004). Consistent with this proposal, studies of recognition memory have found that context-free familiarity is associated with earlier ERP components, such as the N400, relative to the later ERP components typically associated with context-dependent recollection, such as the late positive component (LPC) (e.g., Paller, Kutas, & Mclsaac, 1995, Rugg, Mark, Walla, Schloerscheidt, Birch, & Allan, 1998).

Pulling these two proposals together offers a seemingly straightforward heuristic for using ERP methods to evaluate the mechanisms that underlie NP effects. Specifically, NP effects with early ERP correlates might be attributed to inhibition processes, while NP effects with later ERP correlates might be attributed to episodic binding and retrieval processes. Below, we offer a brief summary of ERP studies of NP, many of which have relied on this heuristic. However, two important shortcomings of this heuristic should be noted prior to considering these studies.

First, it may simply be incorrect to assume that episodic binding and retrieval processes necessarily occur slowly, and therefore ought to be associated with late ERP correlates. Although deliberate, strategic searching of memory that accompanies a great deal of conscious recollection may well occur relatively slowly, and have late ERP correlates, many other behavioural phenomena implicate memory retrieval processes that are rapid and context-specific. For example, contextual cueing effects in visual search (Chun & Jiang, 1998), context-specific proportion congruent effects in Stroop and other distractor interference tasks (Crump, Gong & Milliken, 2006), and context-specific conflict adaptation effects in distractor interference tasks (Spapé & Hommel, 2008) all suggest that context-specific learning and memory retrieval

processes mediate visual attention processes quickly and automatically after stimulus onset. These findings are also consistent with models of instance retrieval (e.g., Logan, 1988), which argue for rapid and automatic retrieval of prior instances, and together point to a need for additional research on the timing of ERP correlates of episodic binding and retrieval.

Second, and most relevant to the dual process proposal described above, there are actually two different "inhibition" frameworks that might be evaluated using ERP methods. On the one hand, the inhibition framework that has guided most research on NP is the distractor inhibition framework. By this view, inhibition is directed at processing of distractors to amplify target processing relative to distractors. Importantly, this framework assumes that targets are subject to very different processing than distractors, and therefore an ERP correlate of NP that taps this inhibition process ought to be unique to IR trials. On the other hand, the dual process framework introduced above assumes that an inhibition process biases attentional orienting in favour of novel events, that this process affects the processing of both IR and AR trials (Houghton & Tipper, 1994), and that this process operates together with episodic binding and retrieval processes to determine priming effects (Christie & Klein, 2001; Milliken et al., 2000). According to this alternative view, an ERP correlate of NP that taps this inhibition process ought to be present for both IR and AR trials.

To address this latter distinction, EEG studies of NP require inclusion of both IR and AR trials, in addition to control trials against which the two repetition conditions can be compared. An ERP correlate of the NP effect that is unique to the IR condition would then point to a different inhibition mechanism than an ERP correlate that is shared by both the IR and AR conditions. Specifically, if an ERP correlate were to occur for both IR and AR trials, it might be attributed to stimulus repetition generally, and perhaps to fundamental issues related to serial

ordering of behaviour, rather than to repetition of a previous distractor as a target (see Houghton & Tipper, 1994). In the following review of ERP studies of NP, we have paid particular attention to this distinction, as we view it as critical to evaluating dual process accounts of NP.

ERP studies of identity-based negative priming

Several studies have found ERP correlates of identity-based NP in early frontal components (Frings & Groh-Bordin, 2007; Gibbons & Stahl, 2010; Hinojosa, Pozo, Méndez-Bértolo, & Luna, 2009). However, there is disagreement across studies in whether this early frontal component is specific to NP, or reflects a more general stimulus repetition component. In particular, Frings and Groh-Bordin (2007) found an enhanced N200 component in mid-frontal regions on IR trials relative to control trials, whereas a more posterior N200 appeared to be associated with the contrast between AR and control trials. Moreover, this NP correlate was significant for the subset of participants who produced a NP behavioural effect, but not for the participants who failed to show a NP behavioural effect. They argued that these results favour an inhibition account of NP (see Hinojosa et al., 2009 for a similar argument). However, using a similar procedure, Gibbons and Stahl (2010) found a decreased P2 and an enhanced N2 for both IR and AR trials. As a result, they attributed these components to processes that are sensitive generally to prime-probe similarity (P2) and retrieval of prime information (N2). Given the inconsistent findings from these studies, at this point it remains unclear whether there is an early frontal ERP correlate of the processes responsible for NP that is unique to NP and not shared with AR effects.

Several studies using visual stimuli have also found P300 differences between IR and control trials (Behrandt et al., 2010; Gibbons 2009; Groh-Bordin & Frings 2009; Kathmann, Bogdahn, & Endrass, 2006; Stahl & Gibbons 2007). The first of these studies was reported by Kathmann et al. (2006), who had participants complete a number discrimination task with target and distractor numbers overlaid over one another. Although the authors attributed the increased P300 on IR trials to more effortful stimulus evaluation required to overcome inhibition from the previous display, a key to interpreting this P300 difference is again whether a similar difference is observed for AR trials. Unfortunately, Kathmann et al. did not include AR trials in their study. Subsequent studies that did include both IR and AR conditions have reported similar P300 effects for both. For example, Stahl and Gibbons (2007) found a decreased left posterior P300 in both IR and AR trials, relative to control trials. They suggested that this effect reflects the processing of prime-probe similarities, and is consistent with retrieval accounts of negative priming (see Gibbons, 2009 for a replication of this finding, and see Behrandt et al., 2010 for a similar result using a picture identification task).

Another late component that has been associated with retrieval explanations of NP effects is the LPC. For example, using a picture identification task (Tipper, 1985), Behrandt and colleagues (2010) found a decreased left posterior P300 for both IR and AR trials relative to control trials, as well as an increased LPC for IR trials only. These authors suggested that the increased LPC reflected effortful cognitive control and retrieval processes engaged when there is a mismatch between the prime and probe displays. This explanation must be regarded as tentative, as the effect has not been replicated, and in fact, the opposite result has been found in studies examining auditory NP effects – Mayr and colleagues reported reduced LPCs on IR trials relative to AR and control trials (Mayr et al., 2003; Mayr, Niedeggen, Buchner, & Orgs, 2006).

In addition to studies examining differences in the amplitudes and latencies of ERP components for IR and control trials, differences between these trials have also been reported with respect to lateralized readiness potentials (LRPs) (Frings, Bermeitinger, & Gibbons, 2011; Gibbons 2006; Gibbons & Stahl 2008; Gibbons 2009). LRPs are thought to reflect the preparation of motor activity on the left versus right side of the body (Coles, 1989), and have been used to examine whether processing on IR trials is influenced by the congruency between the response side required on prime and probe displays. In one study, Gibbons and Stahl (2008) used a flanker design and found that when a pair of prime and probe trials required different response hands, stimulus-locked LRPs were delayed for IR trials relative to control trials, while the reverse was true on pairs of trials in which responses to the prime and probe were made with the same response hand (see also Gibbons, 2009). Gibbons and Stahl argued that this influence of prime-probe response congruency on LRPs supports retrieval accounts over inhibition accounts; the response made on the previous trial was likely retrieved and sped up response selection when the prime and probe required the same hand, and interfered with response selection when the two responses were made with different hands. Gibbons and Stahl also argued that this finding is inconsistent with the idea that a do-not-respond tag is retrieved during probe processing, and that this result instead supports the prime-response retrieval account proposed by Rothermund, Wentura, and De Houwer (2005). Interestingly, Frings and colleagues (2011) replicated this finding in another task in which for every prime-probe pair, participants were told to withhold their response to the prime stimuli until after they had made their response to the probe. This latter finding suggests that stimulus-response bindings can be formed in the absence of response execution, and that these bindings can still influence later probe performance.

ERP studies of location-based negative priming

Less work has examined ERP correlates of location-based NP effects, but a relatively consistent set of results has emerged across these studies. Reduced P1 and/or N1 components in posterior areas (Gibbons, Rammsayer & Stahl, 2006; Kathmann et al., 2006; Kehrer et al., 2009; Ruge & Naumann, 2006), a reduced N1pc component in posterior areas (Gibbons, Wiegleb & Stahl, 2013; Kehrer et al., 2009), an enhanced N2 in posterior areas (Gibbons, 2006; Ruge & Naumann, 2006), and an enhanced N2pc in posterior areas (Gibbons et al., 2013; Kehrer et al., 2009; Ruge & Naumann, 2006), for IR relative to control trials, have all been reported in more than one study. If we follow the assumption that early posterior components favour an inhibition account, then there would appear to be plenty of evidence for such an account.

However, as noted above, this inference requires a comparison to an AR condition to ensure that these components are not simply related to stimulus repetition generally. Unfortunately, most of these studies did not report such comparisons. One study that did report this comparison found early posterior components that were similar for IR and AR trials (Gibbons, Rammsayer & Stahl, 2006). These researchers concluded that the mechanisms responsible for inhibition of return also contribute to location-based negative priming (see also Christie & Klein, 2001; Milliken et al., 2000; Houghton & Tipper, 1994; but see Buckolz et al., 2012). Thus, as with identity-based negative priming, additional work is needed to clarify whether there are early components that are uniquely related to IR effects, rather than shared with AR effects.

With respect to later components, a reduced P300 has been reported in several studies (Gibbons 2006; Gibbons et al., 2006; Gibbons et al., 2013), and has generally been interpreted as

consistent with an episodic retrieval account. The idea here follows from the view that the P300 taps into context updating (Donchin & Coles, 1988). If we assume that the updating of existing event representations constitutes a form of context updating, then it follows that less updating may be required for IR than for control trials.

Together, the combination of both early and late ERP correlates of NP is consistent with the preliminary assumptions introduced earlier, that early ERP components must be inhibition-related and later components are episodic retrieval-related. However, a recent study by Gibbons et al. (2013) takes a very different stance. They found that the ERP correlates of location-based NP were entirely different for a task that included probe distractors and a task that did not include probe distractors. For the probe distractor-absent condition, IR trials were associated with both a reduced P100 amplitude, and a reduced and broadly distributed P300. Conversely, NP in the probe distractor-present condition was associated with an enhanced N2pc in a group of participants showing strong NP effects. Importantly, they attribute both P100 and P300 correlates for the probe distractor-absent condition to episodic retrieval mechanisms, and the N2pc effect for the probe distractor-present condition to inhibition processes. In effect, they depart from the view that early components must reflect inhibition processes, while later components reflect episodic retrieval processes. Instead, they conclude that location-based NP can be produced by both sets of processes, that the task structure dictates which of those processes drives performance, and that episodic retrieval involves both early and late components.

Summary

It is clear that there are both early and late ERP correlates of both identity-based and location-based NP. To distinguish between the two inhibition frameworks described at the outset of this section, additional work is needed to establish the extent to which early components are uniquely associated with IR effects, rather than shared with AR effects. Additional work is also needed to establish whether there is a set of ERP correlates that would distinguish between inhibition and episodic retrieval accounts, as at present it seems that there is substantial variability across studies in how the ERP components are interpreted. Of particular importance is future research aimed at the time course of context-specific retrieval processes, as there appear to be differing views on whether early ERP correlates could possibly tap episodic binding and retrieval. Nonetheless, we view ERP research on NP as a promising avenue to address the multiple process conundrum introduced to the NP literature over 20 years ago. Compelling data that constrain multiple process interpretations of NP (e.g., Gibbons et al., 2013) appear to be what the field needs.

Conclusion

The paper published in 1985 was relatively simple in terms of experimental technique and appeared to make a straightforward contribution to theory. That is, the priming procedure was a variation on other approaches, and the effect – that processing of a previously ignored distractor was impaired when it became the target on the following trial – was straightforward. Similarly, the explanation for the negative priming effect seemed relatively obvious and uncontroversial at the time. That is, the internal representations of irrelevant stimuli that were competing with relevant stimuli for the control of action were actively inhibited. Hence subsequent processing of a stimulus requiring the inhibited representations was impaired.

There was initial promise that a number of important issues could be tackled within the negative priming framework. Take for instance the issue of the frame of reference within which attention functions. Various negative priming studies demonstrated that the medium of attention was not only spatial; rather, it appeared that attentional inhibition could be associated with objects that moved through space; it could be action-centred, changing as the starting point of a reach changed; and it was flexible, selectively inhibiting those representations that were directly competing with the action goal. These contributions concerning the frame-of-reference within which attention functions still stand today.

Similarly, there was early promise that the effect would aid our understanding of the cognitive processes in populations such as older adults, children, and those with schizophrenia and Alzheimer's disease, where declines in inhibitory control had been hypothesized. However, over the subsequent years this simplicity has dissolved, as there is less clear evidence for individual differences than originally appeared to be the case, and the simple inhibition account has been challenged by competing accounts and research findings. The emergence of theoretical accounts based on episodic binding and retrieval processes was particularly problematic to this research area. The idea that a single empirical phenomenon might be driven by more than a single underlying mechanism made the mapping between behaviour and population differences massively more complex. If two or more processes contribute to the NP effect, and if the relative contributions of those processes can vary in response to subtle shifts in stimulus or task properties, then mapping the NP effect to individual differences in any one of those processes may well be an insurmountable task without some conceptual refinement.

The needed conceptual refinement very likely requires additional task analysis. In other words, we might start by admitting that the past 30 years has taught us that the conventional NP

task is not so simple after all. Instead, it is wonderfully (not dreadfully!) complex – but in need of being carved at the joints to gain a clear view of how multiple processes combine to affect behaviour. Combining behavioural methods with brain imaging tools offers a potentially promising path forward, and we highlighted research on ERP correlates of the NP effect here as an example of a field that has met the multiple process challenge head on. At the same time, there are barriers to progress within that literature as well, such as an incomplete understanding of when and where ERP correlates of episodic binding and retrieval processes might be observed. Basic research issues such as this one seem like ripe territory for future work.

Although we have encouraged the view that the multiple process complexity of tasks used to measure the NP effect is a challenge worth taking on, it might be argued instead that task complexity is a burden better avoided, perhaps by moving on to study some entirely different behavioural phenomenon more likely to be process pure. We suspect that this reply would turn out to be folly, as it isn't just the NP task that is complex – much of cognition is complex. Task effects that are driven by multiple processes rather than a single process are likely the norm in cognition.

From this perspective, it can be argued that there are some broadly important lessons about cognition to be learned from 30 years of research on the NP effect. At the same time, research on the NP effect has also offered some specific lessons to researchers in the attention and performance field. In the early 1990's it was proposed that episodic memory retrieval contributes to NP effects (Neill et al., 1992), and the following 20 years saw similar proposals in literatures on task switching (Allport & Wylie, 2000; Waszak, Hommel & Allport, 2003), inhibition of return (Tipper, Grison & Kessler, 2003; Wilson, Castel & Pratt, 2006), conflict adaptation (Spapé & Hommel, 2008), priming of popout (Hillstrom, 2000; Huang, Holcombe &

Pashler, 2004; Thomson & Milliken, 2013), and stop signal inhibition (Verbruggen & Logan, 2008), to name a few. It seems likely that theoretical developments in the NP literature played some role in the direction taken in these other literatures, even if only to point out the utility of instance theory to the attention and performance domain (see also Brooks, 1978; Hintzman, 1986; Jacoby & Brooks, 1984; Logan, 1988; Medin & Schaeffer, 1978).

Ultimately, a satisfactory answer to the original curiosity-driven questions about the role of inhibition in cognition will likely require us to embrace the full complexity of interplay between memory and attention. If we dare to take on the most complex problem in science, and attempt to understand the human brain, then even seemingly simple experimental questions will reveal truly challenging problems.

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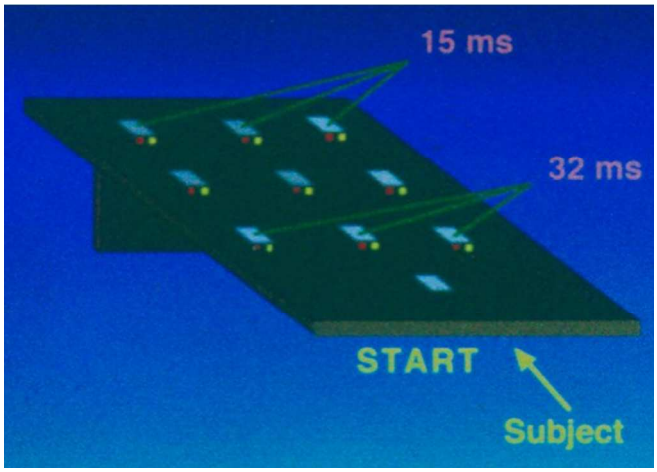
Panel A



Panel B

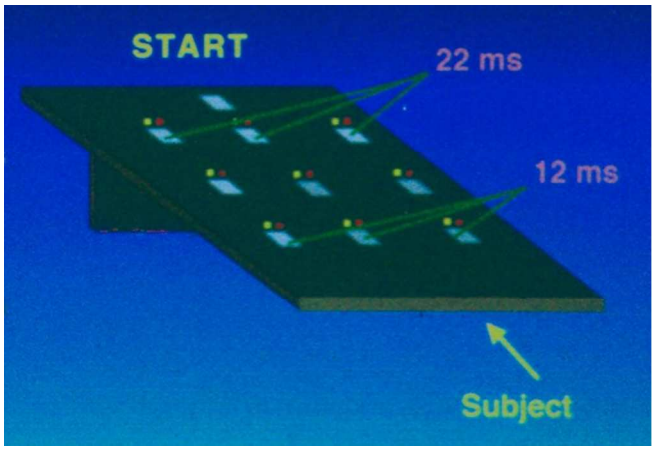


Figure 1

This demonstrates the experimental lay-out and presents the negative priming effects (the difference between a baseline control and a trial where the previous distractor stimulus becomes the next target). Panel A shows the situation where the participants hand started trials at the front of the board and they reached out away from the body to hit the key adjacent to the red target LED while ignoring a green distracting LED. Negative priming was much larger when the previous distractor was near the hand (32ms) than far from the hand (15ms) Panel B shows the situation where the participant starts the reach from the back of the stimulus board, reaching back towards the body. In this case greater negative priming (22ms) is observed when a previous distractor is far from the body but near the responding hand. "Subject" shows the position of the participant, which remained constant in these two kinds of reaching trials, hence maintaining retinotopic, head and body-centred frames of reference while the hand changed location.

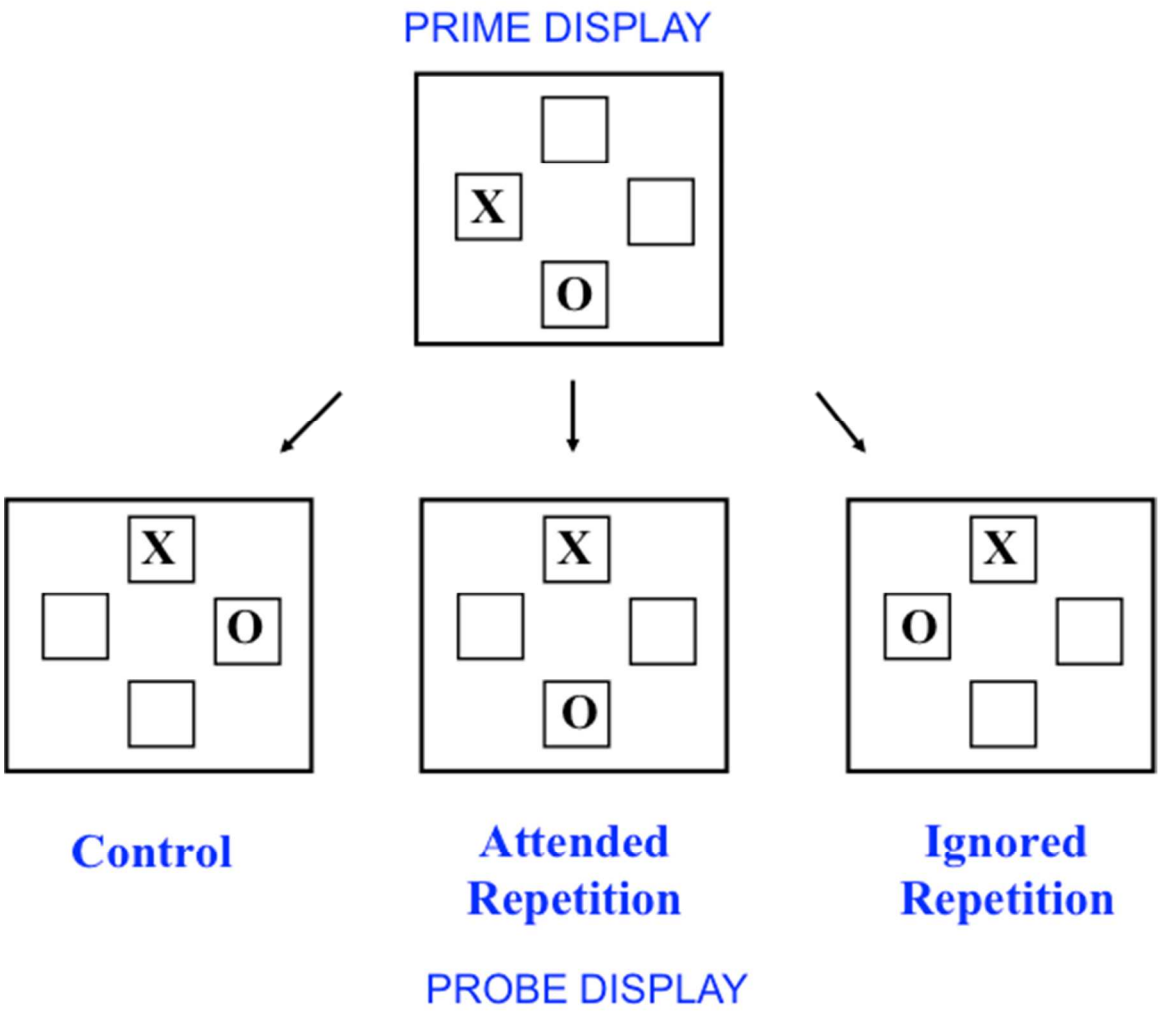


Figure 2

The location-based (or spatial) negative priming procedure. Participants in this task are required to indicate the location of the target O in both the prime (top stimulus display) and probe (bottom three stimulus displays). In the critical ignored repetition (IR) condition, the probe target O appears in the location of the prime distractor X. In the attended repetition (AR) condition, the probe target O appears in the location of the prime target O. In the control condition, the probe target O appears in a previously unoccupied location.